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NASA TN D-2444

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HYDROSTATIC STABILITY OF THE LIQUID-VAPOR INTERFACE IN A LOW-ACCELERATION FIELD

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • AUGUST 1964

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SUMMARY

As a part of the overall study of the behavior of rocket engine propellants stored in space vehicle tanks while exposed to weightlessness, a study was conducted to determine the hydrostatic stability characteristics of the liquid-vapor interface in a cylindrical container when subjected to low acceleration disturbances (less than 1 g) applied parallel to the longitudinal axis of the cylinder.

The Bond number criterion, a dimensionless parameter consisting essentially of the ratio of acceleration to capillary forces, was found to be valid for predicting the regions of hydrostatic stability of the liquid-vapor interface. The critical Bond number delineating the stable and unstable regions was independent of the applied acceleration field and was verified to be 0.84 for solid-liquid-vapor systems possessing 0° contact angles.

INTRODUCTION

The NASA Lewis Research Center is currently conducting an investigation of the phenomena associated with the behavior of liquid rocket-engine propellants stored in space-vehicle tanks that are exposed to weightlessness (zero-gravity) during coasting periods. The stable equilibrium configuration of the liquid-vapor interface has been predicted by analysis (refs. 1 to 3) and has been experimentally determined (refs. 4 to 7). The preceding analytical and experimental studies have considered the static equilibrium configuration of the liquid-vapor interface for conditions under which no external accelerations disturbed the system after thrust cutoff. Realistic space vehicles, however, will be subjected to a number of acceleration perturbations as missions grow more complex. Orientation maneuvers, shutdown transients, vehicle separations, rendezvous dockings, crew and equipment movement, and even atmospheric drag in low Earth orbits are typical of the operations that may well displace the propellant from the desired location. In general, these disturbances will occur at all angles to the vehicle thrust axis and will tend to disrupt the established liquid-vapor interface and cause vapor to move in the direction of the acceleration.

The results of an experimental investigation, conducted at 1 g (ref. 8), of the hydrostatic stability characteristics of the liquid-vapor interface in a cylinder verified the contention that the Bond number criterion (the ratio of acceleration to capillary forces) is valid for determining the regions of interface stability. The investigation established further that the numerical value of the critical Bond number at which instability of the liquid-vapor interface occurs depends on the direction of the gravitational field with respect to the interface. The absolute value of the critical Bond number varied from 0.84 when the cylinder was at a 180° orientation to the gravitational field to essentially infinity for a 0° orientation. The results in reference 8 were obtained by using the Earth's gravitational field to provide the acceleration disturbance; hence, the Bond number criterion was shown to be valid at one value of acceleration, 980.2 centimeters per second squared. In order to verify completely the Bond number criterion the functional relation of acceleration must be validated.

The purpose of this report is to present the results of an experimental investigation of the hydrostatic stability of the liquid-vapor interface in a low-acceleration field (less than 1 g). The acceleration was applied coincident to the longitudinal axis of a cylinder, normal to the liquid-vapor interface, and positively directed from the vapor to the liquid. The investigation was conducted to verify the Bond number criterion as a function of acceleration and liquid parameters and thus to verify that the critical value of the Bond number at which instability of the liquid-vapor interface previously occurred (ref. 8) is a constant independent of the applied acceleration field. This experimental investigation was conducted in a zero-gravity drop-tower facility to allow the liquid-vapor interface to form its zero-gravity equilibrium configuration and to provide a proper environment for the creation of the desired low-acceleration fields.

BOND NUMBER CRITERION

The Bond number criterion, consisting essentially of the ratio of acceleration to capillary forces, can be formulated as

$$Bo = \frac{\Delta\rho a R^2}{\sigma} \tag{1}$$

where Bo is the Bond number, $\Delta\rho$ is the density difference between the liquid and vapor phases, a is the applied acceleration field, R is the radius of the cylindrical geometry, and σ is the liquid-vapor surface tension. The density of the vapor phase is frequently neglected, and the Bond number is defined as

$$Bo = \frac{aR^2}{\beta} \tag{2}$$

where β is the specific surface tension. The results of the experimental investigation reported in reference 8 yielded a critical value for the Bond number of 0.84 for one value of acceleration, the acceleration field due to gravity. This value was obtained when the acceleration was directed from the vapor to the liquid phase, normal to the liquid-vapor interface. The data for solid-liquid-vapor systems possessing 0° contact angles (ref. 8) are shown in figure 1. The critical diameter at which instability occurred (generally characterized by a breakage of the interface and by a flow of liquid from the cylin-

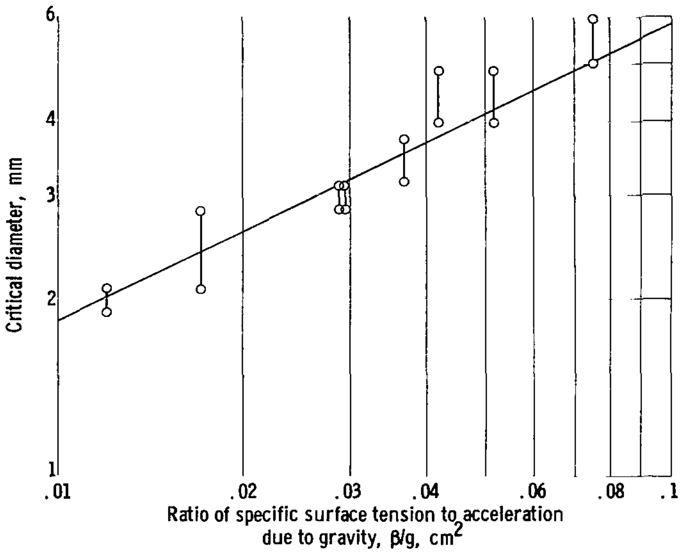


Figure 1. - Stability characteristics in vertical cylinder at 1 g.

der) was a function of the specific surface tension of the liquid; the gravitational acceleration was constant for the experiment. The value of the critical Bond number thus defines the regions of hydrostatic stability of the liquid-vapor interface for the cylinders investigated and the direction of the applied gravitational acceleration.

The study in reference 8 and the present investigation necessitate the analogy between the gravitational-body-force density ρg imposed on a column of liquid in a capillary tube and the inertial acceleration field imposed on a propellant tank in a weightless environment. If the Bond number is a linear function of acceleration, the equation for the critical Bond number becomes

$$Bo_{cr} = 0.84 = \frac{aR^2}{\beta} \tag{3}$$

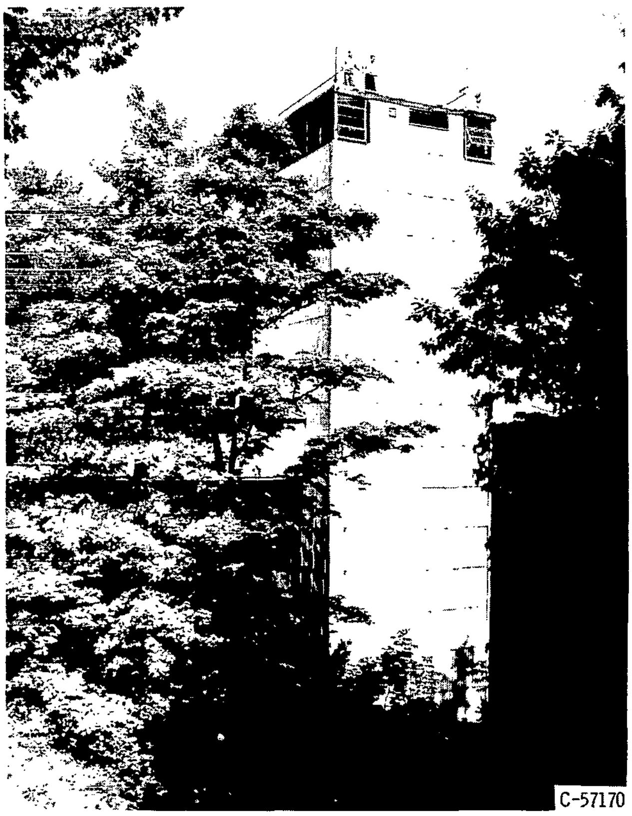


Figure 2. - 100-Foot drop tower.

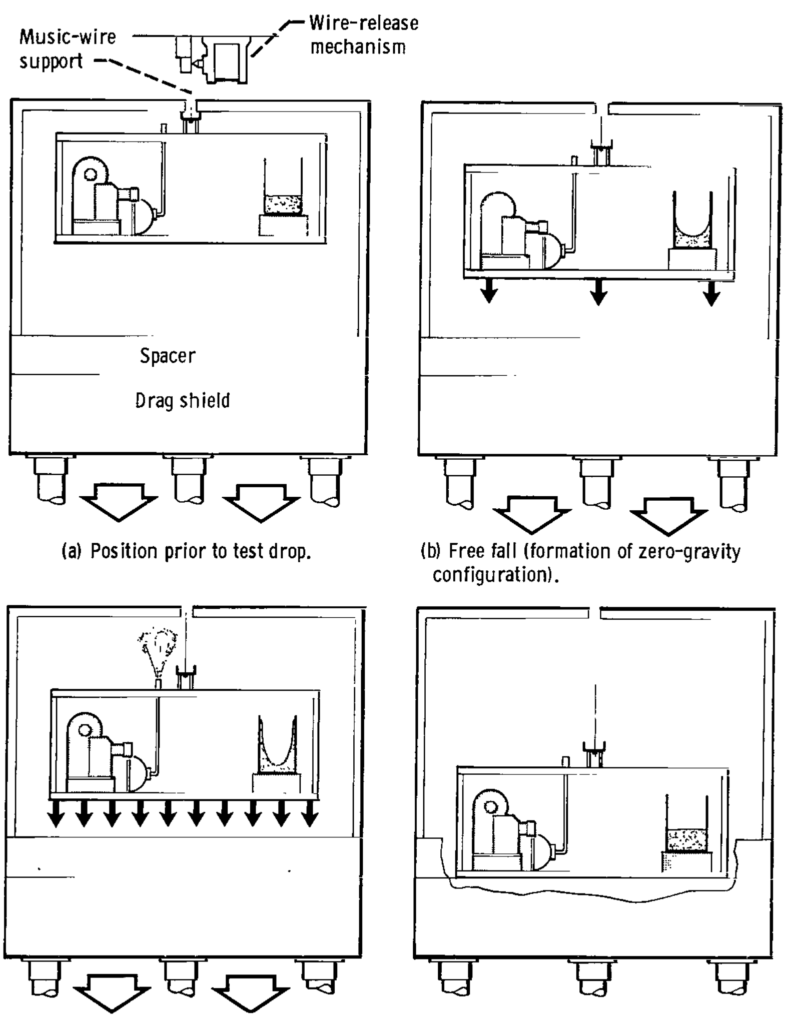
Because of the common stabilizing parameter of the liquid-vapor surface energy, the critical Bond number in equation (3) should be independent of the form of the acceleration field. Although the actual process of the disruption of the liquid-vapor interface in each particular acceleration field may require a more elaborate physical description, it appears to be immaterial from the point of view of the liquid-vapor interface whether the containment geometry or the liquid is accelerating because the relative motion between the two is completely unaffected.

In order to verify this contention, acceleration levels of approximately 0.1 and 0.01 g were used to extend the stability characteristics obtained in reference 8. The actual accelerations used in this study, as determined by the calibration procedure, were 83.3±0.39 and 9.80±0.20 centimeters per second squared. The critical radius at which instability occurs was calculated by assuming equation (3) to be valid. Cylinders with radii above and below this value were then employed in the experiment package. The method used to obtain the data resulted in a range of cylinder diameters in which stability or instability was observed.

APPARATUS AND PROCEDURE

Test Facility

The experimental investigation was conducted in the Lewis Research Center drop tower (fig. 2), which provides a usable drop distance of 85 feet, or 2.3 seconds of unguided free fall. In this facility, air drag on the experiment package is kept below 10^{-5} g by allowing the package to free fall inside a protective drag shield. The drag shield is designed with a high ratio of weight to frontal area and a relatively low drag coefficient so that the deviation from true free fall would be minimized. The relative position of the experiment package with respect to the drag shield during a test drop is presented in figure 3. The experiment package and the drag shield fall simultaneously, yet are completely independent of each other during the drop. To compensate for the added distance the package travels relative to the drag shield because of the low accelerations imposed on the package, spacers were added to the drag shield (fig. 4).

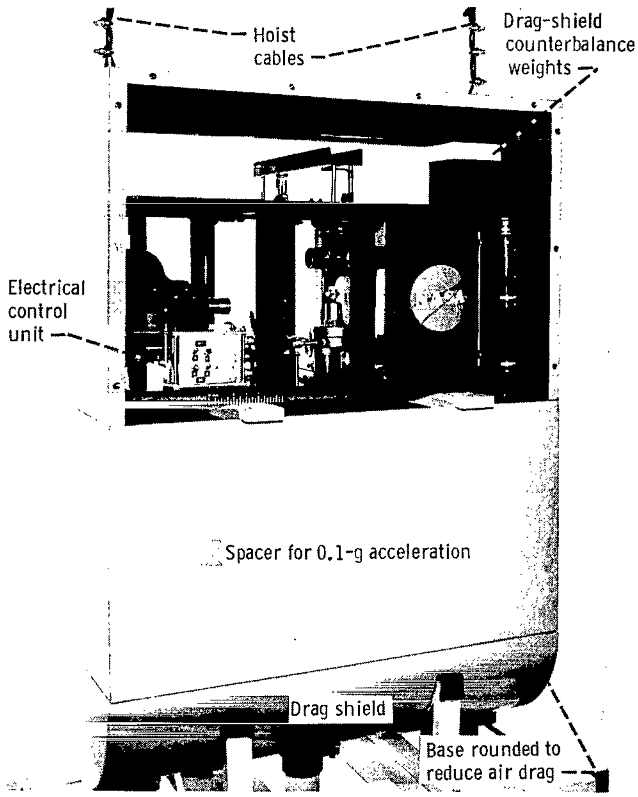


(a) Position prior to test drop.
(b) Free fall (formation of zero-gravity configuration).
(c) Application of low-acceleration field.
(d) Position after test drop.

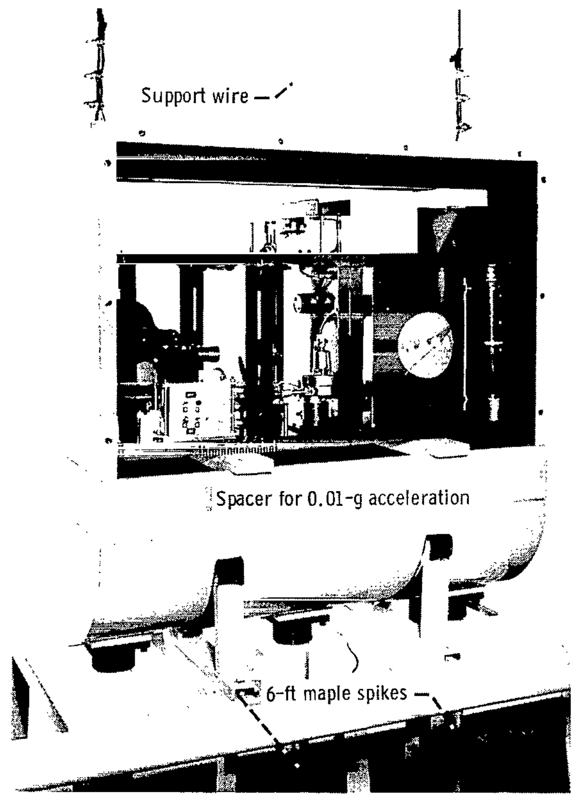
Figure 3. - Schematic drawing showing sequential position of experiment package and drag shield before, during, and after test drop.

Experiment Package

The experiment package (fig. 5) is a self-contained unit equipped to recover photographic data. Borosilicate glass cylinders containing the test liquid are



(a) 0.1-g assembly. C-66769



(b) 0.01-g assembly. C-66770

Figure 4. - Experiment package in air-drag shield.

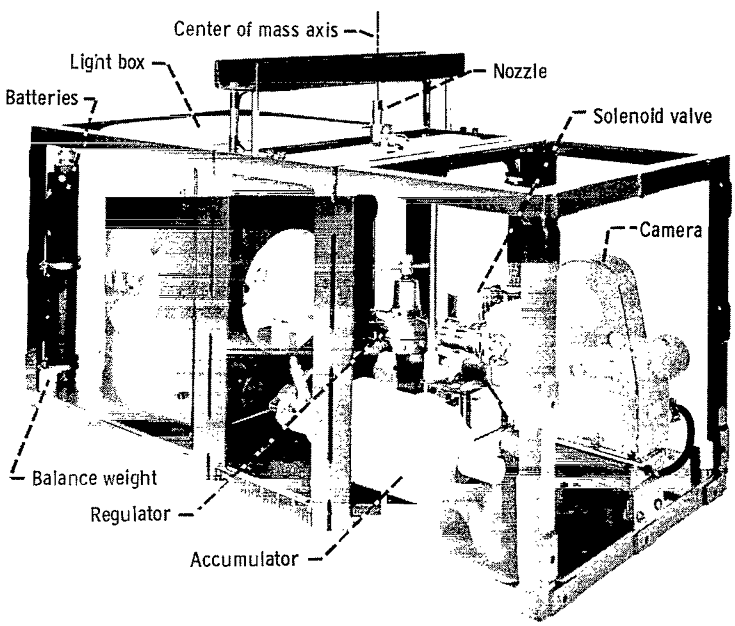


Figure 5. - Experiment package.

suitably mounted in a box having a dull white interior and are indirectly illuminated to allow a 16-millimeter high-speed motion-picture camera to photograph the liquid behavior during the drop. Low accelerations are imposed on the experiment by expelling compressed nitrogen gas from a thrust nozzle located on top of the package so that the thrust axis is coincident with the center-of-mass axis. The thruster system consists of a high-pressure accumulator, a pressure regulator, and a solenoid valve. Power to operate the lights, camera, and solenoid is obtained from rechargeable nickel-cadmium batteries carried on

Liquid	Density at 20° C, ρ, g/cm³	[a]Surface tension at 20° C, σ, dynes/cm	Specific surface tension, $\frac{\text{surface tension}}{\text{density}}$, σ/ρ, cm³/sec²
Trichlorotrifluoroethane	1.579	18.6	11.78
Carbon tetrachloride	1.595	26.8	16.79
Ethanol, anhydrous	.7893	22.3	28.25
[b]Ethanol, 10 percent	.9847	49.6	50.37

[a]Vapor phase, air.

[b]Percentage composition by volume with distilled water.

the experiment package.

Test Liquids

The liquids used and their physical properties pertinent to this study are given in the table at the left. Most rocket-engine propellants have 0° contact angles on the types of tank materials currently being employed in rocket vehicle design; therefore, test liquids were chosen that have a 0° contact angle with borosilicate glass. A small quantity of dye was added to each test liquid to improve photographic quality; the addition had no measurable effect on the liquid properties.

Operating Procedure

Prior to each test drop, the experiment package was carefully balanced to locate the center-of-mass axis on a line coincident with the thrust axis (fig. 5). The magnitude of the thrust was determined by means of the thrust calibration system shown in figure 6. The experiment package was placed on a frictionless air bearing so that the thrust was incident on a load cell mounted in line with the nozzle. Since a physical connection to the package would introduce a drag factor, the solenoid valve was actuated by a transistorized photoresistive switch in the electrical control unit.

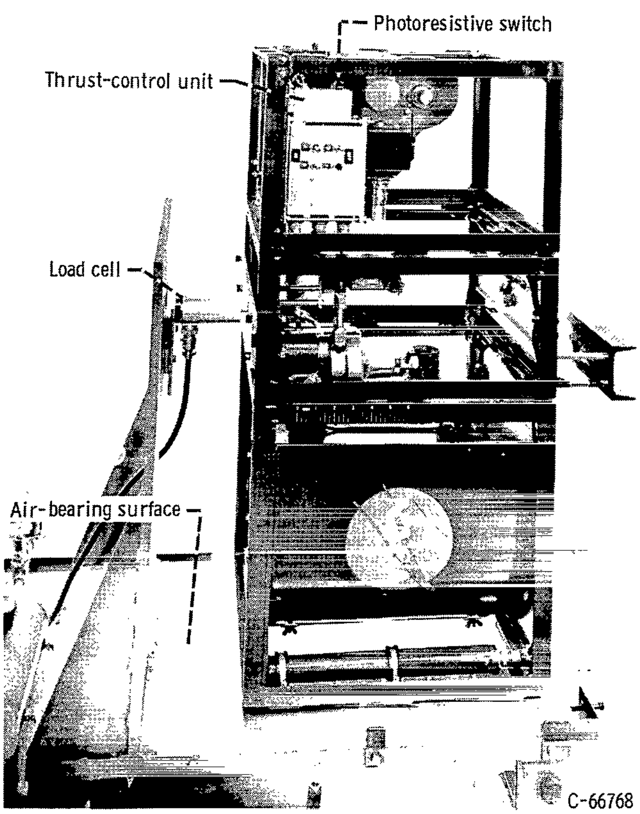


Figure 6. - Thrust calibration system.

Contamination of the glass surfaces and liquids, which could alter the surface tension and contact angle of the test liquid, was carefully avoided. A preliminary cleaning of the glassware in a detergent solution was followed by an immersion in hot chromic acid and finally by an ultrasonic cleaning in a solution of detergent and distilled water. The cylinders were then rinsed in distilled water, dried in a warm air dryer, and filled to the desired level with the test liquid.

After the cylinders were mounted in the light box, the experiment package was placed inside the drag shield. The entire assembly, consisting of the drag shield and the experiment package, was counterbalanced (fig. 4) because the center of mass of the experiment package was located 2 inches off the vertical geometric axis. The counterbalancing ensured that the drag shield and package would not tilt when suspended from the support wire on the eighth floor. Rotation of the drag shield due to the nonsymmetric mass distribution during the fall was negligible. Initiation of free fall was accomplished by pressurization of an air cylinder that forced a knife edge into the support wire and caused the wire to fail. The application of the acceleration thrust was preceded by a 1-second time delay to allow the interface to form its zero-gravity configuration. This time was generally not sufficient to ensure the complete absence of oscillatory interface motion toward the unique time-independent, zero-gravity interface configuration. The time, however, was adequate to allow for sufficiently damped interface motion so that, when the low-acceleration field was applied to the experiment, the subsequent behavior of the interface was not observably influenced by residual transient effects. For the range of cylinder diameters and liquid properties used, the 1-second formation time was a suitable compromise between an adequate formation period and a sufficient time in the low-acceleration field to observe stability or instability.

RESULTS

The results of the investigation are shown in figure 7, where the observed stable and unstable diameters are plotted as a function of the ratio of specific surface tension to acceleration. The criterion for stability under the imposed acceleration was that the interface configuration be independent of time, or that the velocity at every point on the liquid-vapor interface be zero, that is, that the interface configuration remain identical to the static zero-gravity equilibrium configuration. Conversely, the criterion for instability was that the interface configuration be time dependent during the entire duration of the applied acceleration; the finite liquid-vapor interface velocity indicates the disruption of the interface.

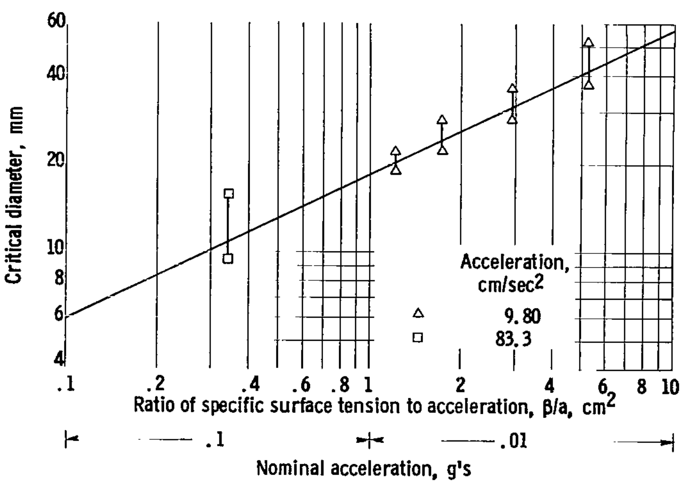


Figure 7. - Stability characteristics in a cylinder at low-acceleration fields.

Although the dynamic behavior of the disruption of the

(a) 1-g configuration.

(b) 0-g configuration.

(c) 0.01-g configuration; acceleration applied for 1.09 seconds; cylinder 1 remains stable; cylinder 2 is unstable.

Figure 8. - Interface stability of trichlorotrifluoroethane with critical diameter of 20.1 millimeters. Acceleration, 9.80 centimeters per second squared; diameter of cylinder 1, 19.05 millimeters; diameter of cylinder 2, 26.3 millimeters.

liquid-vapor interface was not of immediate interest in this investigation, it was apparent from the analysis of the photographic data that the velocity of the interface when instability did occur was a function of the Bond number. For a particular set of data points, the only variable in the experiment was the diameter of the cylinders. The larger the diameter (i.e., above the critical diameter as calculated from eq. (3)), the greater the observed distortion of the interface; therefore, as the critical diameter was approached negatively, the observed velocity and total distortion of the interface became smaller. In order to avoid any possibility that the instability phenomenon was of a transient nature, as observed in the limited time available for the applied acceleration (i.e., where the equilibrium zero-gravity configuration may possibly tend to re-form in time despite the applied acceleration), a total distortion of the interface configuration of a minimum of 1 diameter was adopted as an adequate criterion for instability. The diameter indicative of this criterion for instability was, therefore, the only value plotted.

The curve in figure 7 is that of equation (3), and under the stipulations attached to the sets of data points, the curve properly delineates the regions of hydrostatic stability of the liquid-vapor interface. Representative photographs illustrating the hydrostatic stability of trichlorotrifluoroethane under an imposed acceleration of 9.80 centimeters per second squared are shown in figure 8. The critical diameter, obtained from equation (3), is 20.1 millimeters. Two cylinders, having diameters above and below this value, 26.3 and 19.05 millimeters, respectively, were employed to experimentally obtain the photographs of interface stability phenomena. The bracketing of the critical diameter at which interface instability occurs is unmistakably evident from figure 8(c). The interface configuration in the stable region has essentially remained unchanged from the zero-gravity configuration, and the time independence is indicated by the zero velocity of the interface. The interface configuration in the unstable region indicates a distortion of the interface greater than the diameter of the cylindrical container in the time available for the applied low-acceleration field. The time dependence is exhibited by a finite velocity at each point on the liquid-vapor interface, which causes the liquid to be displaced toward the top of the cylinder. The disruption of the liquid-vapor interface in the unstable region was in all instances symmetrical about the longitudinal axis of the cylinder. The velocity of the unstable interface appeared to be a function of the Bond number calculated by employing the cylinder diameters used in the experiment.

DISCUSSION

Verification of Bond Number Criterion

The preceding results (fig. 7) and those obtained in reference 8 (fig. 1, p. 3) are combined in figure 9. The results of the experimental investigations indicate that the Bond number criterion is valid for predicting the region of hydrostatic stability of the liquid-vapor interface. Correlation of the experimental data points with the curve given in figure 9 verifies that the critical Bond number delineating the regions of hydrostatic stability is a constant independent of the acceleration field. The critical Bond number is properly given by equation (3) for an acceleration applied parallel to the longitudinal axis of a cylindrical geometry and for solid-liquid-vapor systems possessing 0° contact angles.

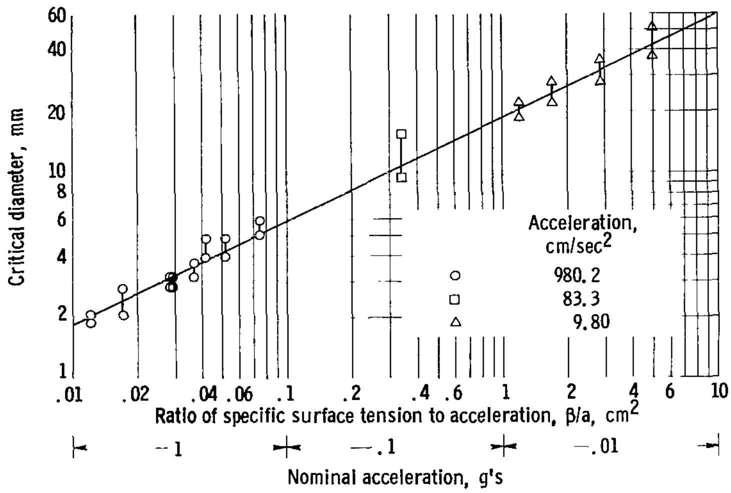


Figure 9. - Interface stability delineated by Bond number criterion.

The arbitrary criterion of instability applied in this experimental investigation indicates a tolerance in the radius of the Bond number criterion. It is believed, however, that if more time had been available during which the low-acceleration field could have been maintained, the criterion of instability would be unnecessary, and cylinders whose radii nominally exceeded the radius calculated from the critical Bond number at a given acceleration field and specific surface tension would have displayed the instability phenomenon. The total disruption of the liquid-vapor interface would occur (although with a small velocity), the entire column of the liquid being ultimately displaced to the opposite side of the cylinder. This belief was substantiated by an analysis of the photographic data wherein finite interface velocities were observed in all the cylinders whose radii exceeded the calculated value given by the critical Bond number, 0.84.

Application

As a result of these investigations, it is now possible to predict the critical acceleration needed to disrupt the zero-gravity equilibrium interface

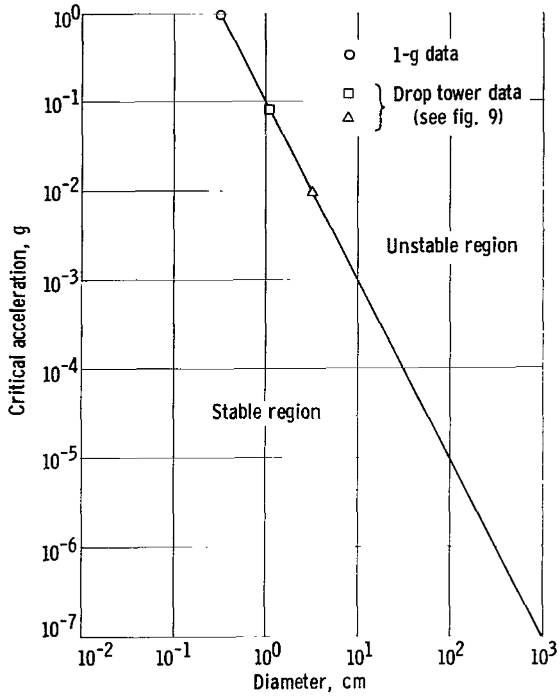


Figure 10. - Interface stability of anhydrous ethanol as function of acceleration. Specific surface tension, 28.25 centimeters cubed per second squared.

configuration in realistic vehicle propellant tanks. In figure 10 a plot is presented of critical acceleration against tank diameter for one liquid that is representative of many propellants. The curve was obtained by applying the Bond number criterion to extend the 1-g data (ref. 8) and the drop-tower data obtained in this study to the tank diameters that are currently under consideration for space vehicles. It can be seen from figure 10 that for space vehicles having tank diameters of the order of 10 feet (304.8 cm) accelerations greater than 10^{-6} g will disrupt the liquid-vapor interface and cause the propellant to be relocated.

SUMMARY OF RESULTS

An experimental investigation of the hydrostatic stability of the liquid-vapor interface in a cylindrical geometry was conducted in a low-acceleration field. Under the stipulations that the applied acceleration field is directed parallel to the longitudinal axis of the cylinder normal to the liquid-vapor interface and that the solid-liquid-vapor system possesses a 0° contact angle, the investigation yielded the following results:

1. The Bond number criterion, consisting of the ratio of acceleration to capillary forces, is valid for predicting the regions of hydrostatic stability of the liquid-vapor interface.

2. The critical Bond number delineating the stable and unstable regions is independent of the applied acceleration field.

3. The numerical value for the critical Bond number at which instability of the liquid-vapor interface occurs is 0.84.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, May 16, 1964

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